Novel Architecture for Preventing Interference between Automation and Pilot Maneuvers

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Abstract

In a pilot/automation interface, it is said that pilots tend to get confused about the unforeseeable behavior of automated airplanes when responding to an abnormal situation; such confusions trigger disasters. For preventing interference between automation and pilot maneuver, this research has proposed a new architecture termed "Human As a Control Module architecture (HACM architecture)". The proposed architecture treats a pilot as one module of controlling aircraft. This paper introduces the HACM architecture and explains the concept and mechanism. The effectiveness of the architecture is confirmed via numerical simulation which mimics the situation of an aircraft accident in the past.

1 Introduction

While automation can reduce the frequency of pilot errors, it is still a potential cause of new types of errors induced by the confusion in pilot/automation interfaces [1–3]. According to reference [2, 3], pilots tend to get confused about the unforeseeable behavior of automated airplanes when responding to an abnormal situation; such confusions trigger disasters. An improvement of the pilot/automation interface is required to avoid conflicting actions taken by pilots and automated systems.

In automation design, there are two main types of approaches for achieving pilot-friendly automation: 1) creation of better environments for pilots to prevent mistakes and 2) adaptive management and modification of inappropriate actions by pilots and/or automatic systems. The first approach includes improvement in the cognitive and decision-making tasks, for example, flight deck and display design, design of flight management systems, etc. Although some of these designs are being used in practice, this approach is not the only solution for pilot-friendly automation. During the design process, the first approach is required to hypothesize how a design coordinates between a pilot and automation. However, it is difficult to define automation designs that support pilots because we might not foresee or understand autoflight systems and pilot behaviors under all circumstances including abnormal situations during flight. Because these conflicts are mainly attributed to the dynamics change of the pilots and automated flight systems during a flight, a context-sensitive support based on the adaptive approaches is required. With the background in mind, this research has proposed a new architecture termed Human As a Control Module (HACM) architecture to advance coordination between automation and pilot maneuver [4]-[7].

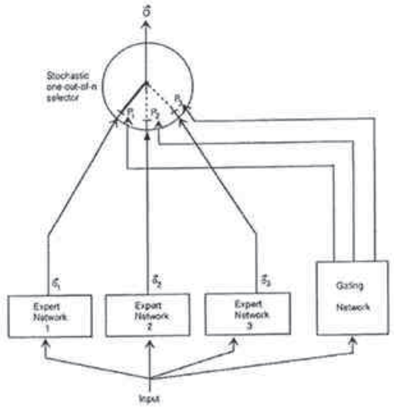
In this paper, the concept and the mechanism of the HACM architecture is explained and the effectiveness is shown via numerical simulation. Firstly, we explain the modular structures of which concept are highly influenced to proposing the HACM architecture. One of the aircraft accidents caused by the interference between automation system and pilot is picked up as to specify the conflicts between automation and pilot. Secondly, the HACM architecture is introduced to show the concept and mechanism. Thirdly, the effectiveness of the proposing architecture is confirmed via numerical simulation which mimics the aircraft accident in the past. Lastly, we conclude the paper.

2 Confliction Between Automated Aircraft and Pilot

Modular Structure in the Human Brain

The modular structure has been proposed to mimic neural circuit of human brain and applied for learning system/controller. As a learning system using modular structure, "Mixture of expert" is well known [8]. As shown in Fig. 1, the multiple module of the expert networks are connected in parallel using the independent gating networks, and the gating networks calculate the weight on the learning parts and the outputs corresponding to the each expert networks. Fig. 2 shows one of the module structures termed "Multiple Paired Forward-Inverse Model (MPFIM)" proposed by Wolpert and Kawato [9]. Multiple pairs of the forward model (Predicted controlled dynamics) and the inverse model (controller) of the controlled dynamics are connected in parallel as shown in Fig. 2. Based on the predicted error values between the forward model and the real controlled dynamics, these modules are adaptively switched, and the selected module contributes to control the dynamics and pursue learning of the forward model.

In this way, these modular structures contribute to control the dynamics by adaptively switching modules (controllers). From this point of view, recent flight control system equipped in aircraft consists of the modular structure. Each module has a controller of which characteristic is different from the others, for example, different values and combinations of feedback gains and target values, flight mode, etc. The appropriate modules are selected depending on the altitude, speed, and the other conditions. It can be said that recent highly



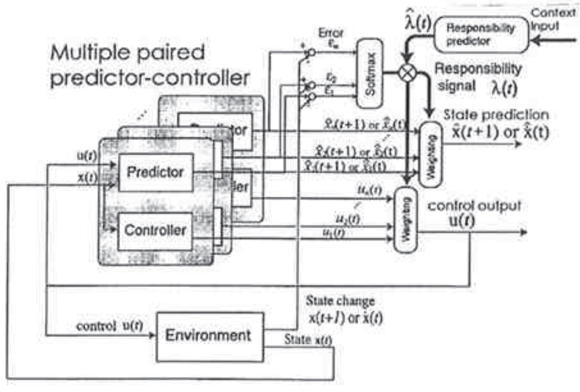


図1 複数予測モデル-制御器対アーキテクチャ
Fig. 1 Schematic diagram of multiple predictor-controller pair architecture.

Fig.1 Mixture of expert [8] Fig.2 Multiple Paired Forward-Inverse Models (MPFIM) [9]

automated aircraft is flying with the artificial intelligence which has modular architecture and the brain of the aircraft consists of various types of flight controllers (autopilot) and pilot operation/control, combination of the artificial intelligence and human brains.

Artificial Intelligence and Human Brain on the Aircraft

The recent aircraft is flying with automatic flight controllers, a kind of artificial intelligence, and pilot, human brain, and it is still a potential cause of new types of accidents/incidents induced by the confusion in pilot/automation interfaces [1–3]. In 2002, a B747-400 flying at around 40,000 ft with autopilot in the Japanese airspace met with atmospheric turbulence [10]. The airspeed dramatically increased and the autopilot changed the flight mode from the altitude control to the speed control and started to control airspeed by changing the pitch angle. The pitch angle was increased by the autopilot to reduce the airspeed, however the airspeed was increased to around V_{mo} (the maximum limitation of the airspeed). Then, the pilot shift to manual control and the pitch angle oscillation was caused by the pilot's elevator control. Because of the vertical oscillation, 4 people were seriously injured and 29 people were slightly injured, and a part of the airborne was damaged. The pilots in the cockpits commented that they had no time to check the information displayed on the monitor and cannot remember whether or not they disconnected the autopilot. In this way, especially in the emergency situation, pilots tend to get confused about the unforeseeable behavior of automated airplanes; such confusions trigger disasters.

How should we resolve the conflicts between the artificial intelligence and the human brain on the aircraft? As one of the solutions, we propose a new architecture termed "Human As a Control Module architecture (HACM architecture) [4]-[7]" and explain the concept and the mechanism in the next section. The HACM architecture is inspired by the modular structure mentioned in the previous section.

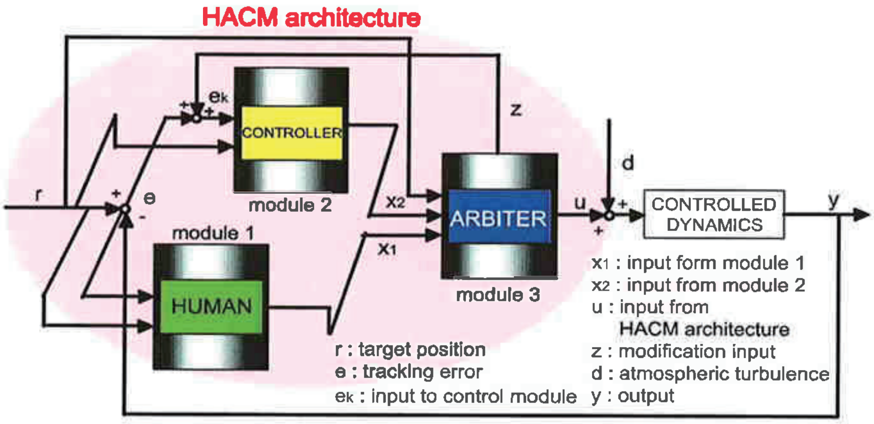


Fig.3 Human As a Control Module architecture

3 Human As a Control Module architecture

3.1 Concept of the HACM architecture

The HACM architecture treats a pilot as a single module for controlling aircraft. Fig.3 shows a block diagram that includes the fundamental structure of the HACM architecture and a controlled dynamics, which in this case is the dynamics of the aircraft. As shown in Fig. 3, the HACM architecture consists of modular structure including a human (pilot) and the basic structure of the HACM architecture comprises three types of modules—the human module, controller module, and arbiter module. The characteristics and roles of each module are described below:

Human module: This module corresponds to pilot. It is difficult to represent pilots using numerical models because pilots flexibly change their dynamics depending on the situation within the bounds of their physiological abilities. It is advantageous for a pilot to assess situations well and track their performance. On the other hand, their physiological ability is limited. In addition, they sometimes make mistakes during cognition and decision making. Humans also tend to take conflicting actions intentionally.

Controller module: This module corresponds to an automatic controller that is appropriately designed with controlled dynamics. The automatic controllers can achieve good performance within the design conditions. The disadvantage is that a trade-off exists between the tracking performance and the robustness toward the disturbance input and modeling error. In addition, the controllers are subject to deteriorating control ability beyond the design conditions. Various design approaches can be applied to this module. This paper precedes discussions on a simple feedback controller because the purpose of this paper is to introduce HACM architecture and confirm its effectiveness.

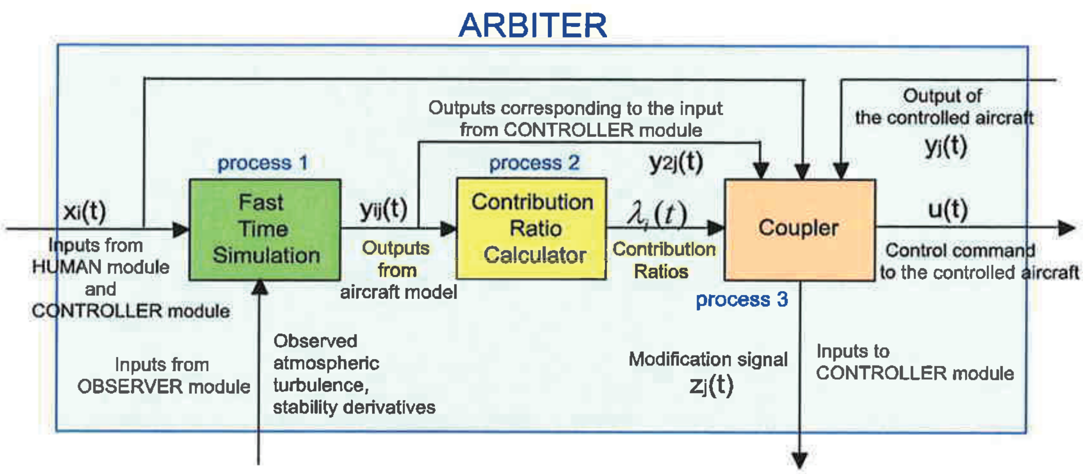


Fig. 4 Arbiter Mechanism

Arbiter module: This module manages inputs $x_i(t)$ $(i=1,2)$ from both the human and controller modules that simultaneously provide control commands to the aircraft. These commands are gated in the arbiter module by the contribution ratios, which are calculated using the softmax function. The contribution ratio represents the extent to which each module presently accounts for the behavior of the controlled dynamics. The role of the arbiter module is to eliminate inappropriate control commands from the other two modules to the controlled dynamics and generate appropriate control inputs that suit the present conditions. Through the arbiter module, the HACM architecture enables us to realize a control system that compensates for the limitations of the human module and controller module and utilizes their advantages in the aircraft control. As a result, the module realizes a backup system that comprises the pilot and the automated controller that have different characteristics as mentioned above. When either the human or controller modules provide irrelevant inputs, the arbiter module ignores the input and provides another suitable one.

3.2 Arbiter Mechanism

Fig. 4 shows the mechanism of the arbiter module that arbitrates the control commands inputted by the pilot (human module) and the autopilot (controller module). As shown in Fig. 4, the control commands, the elevator commands in this paper, from the human module $x_1(t)$ and controller module $x_2(t)$ are inputted to the arbiter module. The general mechanism in the arbiter module comprises the following three processes—a real time simulation, a contribution ratio calculator, and a coupler.

Real time simulation: First, the arbiter module simulates the outputs of the aircraft corresponding to the control commands of both the human and the controller modules online. The arbiter module possesses the dynamic model of the controlled aircraft within its framework. By using the dynamic model, the outputs $y_{ij}(t)$ $(i=1,2 \quad j=1,2,\ldots l)$ for inputs $x_i(t)$ to the aircraft are numerically simulated. l corresponds to the number of outputs from the aircraft model that are used to calculate the contribution ratios in the next process. The values of $y_{1j}(t)$ correspond to the outputs when the control command $x_1(t)$ is inputted to the aircraft model. The values of $y_{2j}(t)$ correspond to the outputs when the control command $x_2(t)$ is inputted to the aircraft model.

Contribution ratio calculator: Second, contribution ratios $\lambda_i(t)$ $(i=1,2)$ are calculated by using the outputs of the aircraft model predicted in the previous process. $\lambda_1(t)$ is a contribution ratio for the human module, and $\lambda_2(t)$ is for the controller module. The contribution ratio represents the extent to which each inputs presently accounts for the behavior of the aircraft dynamics.

In order to calculate the contribution ratio, first, the performance of the pilot and the autopilot are individually quantified. We measure the performances of each control commands based on the following index $E_{ij}(t)$ $(i=1,2 \quad j=1,2,\ldots l)$, which is given by

$$E_{ij}(t) = \frac{\sum_{s=n-m}^{n} \left(\varepsilon_{ij}(t_s)\right)^2 e^{(s-n+m)/m}}{\sum_{s=n-m}^{n} e^{(s-n+m)/m}} \qquad (1)$$

where $\varepsilon_{ij}(t)$ is the error between $y_{ij}(t)$ and target values, which are the desired outputs of the aircrafts at present time t and n is the number of time steps at present time t. In this case, t is equal to t_n. m is the number of time steps of the past tracking errors considered in the index.

In order to calculate $\varepsilon_{ij}(t)$ in Eq. (1), flight envelope protection is applied. In this paper, the flight envelope protection implies that the arbiter module adaptively adjusts the control authority when the human module (pilot) does not control the aircraft to satisfy the defined flight envelope; this envelope defines that the range aircraft safely continues its flight. In this paper, the HACM architecture is applied for longitudinal control of the aircraft, so the flight envelope is defined as follows:

$$
\begin{aligned}
\theta_{\min} &\le \theta_1(t) \le \theta_{\max} \\
\dot{\omega}_{\min} &\le \dot{\omega}_1(t) \le \dot{\omega}_{\max} \\
\ddot{\omega}_{\min} &\le \ddot{\omega}_1(t) \le \ddot{\omega}_{\max}
\end{aligned}
\qquad (2)
$$

where $\theta_1(t)$, $\dot{\omega}_1(t)$, and $\ddot{\omega}_1(t)$ are the outputs of the aircraft model corresponding to the input from the human module calculated in the arbitrating system. As shown in (2), the upper and lower limits are introduced for the pitch angle, vertical acceleration, and rate of vertical acceleration. This paper yields $\theta_{\min} = -11(\deg)$, $\theta_{\max} = 11(\deg)$, $\dot{\omega}_{\min} = -1.0(G)$, $\dot{\omega}_{\max} = 2.5(G)$, $\ddot{\omega}_{\min} = -0.3(G/\sec)$, and $\ddot{\omega}_{\max} = 0.3(G/\sec)$. The upper and lower value of $\dot{\omega}$ is the designated value at which B747-400 flies safely. The limitation of $\ddot{\omega}$ is the rate limitation of the vertical acceleration in the speed control mode of the autopilot in the distressed aircraft. $\varepsilon_{ij}(t)$ is defined as follows:

If $\quad y_{ij}(t) < y_{j\min}$,

$$
\text{then} \quad \varepsilon_{ij}(t) = \frac{y_{ij}(t) - y_{j\min}}{y_{j\min}}. \qquad (3)
$$

If $\quad y_{j\max} < y_{ij}(t)$,

$$
\text{then} \quad \varepsilon_{ij}(t) = \frac{y_{j\max} - y_{ij}(t)}{y_{j\max}}. \qquad (4)
$$

where

$$
\begin{aligned}
& y_i(t) \quad (i = 1,2) \\
&= \left[y_{ij}(t)\right]^T (j = 1,2,3) \\
&= \left[y_{i1}(t), \quad y_{i2}(t), \quad y_{i3}(t)\right]^T \\
&= \left[\theta_i(t), \quad \dot{\omega}_i(t), \quad \ddot{\omega}_i(t)\right]^T.
\end{aligned}
\qquad (5)
$$

$y_1(t)$, the output vector of the aircraft model, corresponds to the input from human module and $y_2(t)$, the output of aircraft model, corresponds to the input from the controller module.

By using the index as shown in (1), the performances of each command are numerically evaluated. The index (1) measures the performances of each input from the human module and the controller module by using the value of errors predicted in the past.

The contribution ratios of each module $\lambda_i(t)$ are calculated by using (1) and the softmax function. The contribution ratios are given as follows:

$$\lambda_i(t) = \frac{\sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}}{\sum_{i=1}^{2} \sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}} \qquad (6)$$

where σ is a scaling constant. In this simulation, we set $\sigma = 10.0$. The softmax function normalizes the tracking errors across the modules so that the contribution ratios lie between 0 and 1 and the sum of the contribution over the modules is 1.

***Coupler*:** Third, the control commands from the human module and the controller module are adjusted and added in this process. The input from the arbiter module $u(t)$ to the aircraft is given as follows:

$$u(t) = \sum_{i=1}^{2} \lambda_i(t) x_i(t) \qquad (7)$$

The input from the human module or the controller module with a smaller error index than that of the other greatly contributes to input $u(t)$. Conversely, the other input has a low contribution to $u(t)$.

Another function of this process is to generate a modification signal $z_j(t)$ $(j = 1,2 \cdots l)$ that is inputted to the autopilot as a feedback signal. In order to avoid high gain feedback, modification signal $z_j(t)$ is defined as follows.

$$z_j(t) = y_{ij}(t) + \lambda_i(t)(y_j(t) - y_{ij}(t)) \qquad (8)$$

$y_j(t)$ is the output of the real aircraft. (8) yields $y_{ij}(t)$ where $\lambda_i(t) = 0$ in order to prevent the autopilot from sensing the other's control input as disturbance. Where $\lambda_i(t) \neq 0$, the modification signal (8) will make the autopilot to stabilize the aircraft movement caused by the interference of the inputs the human module or the controller module gives.

4 The effectiveness of the HACM architecture

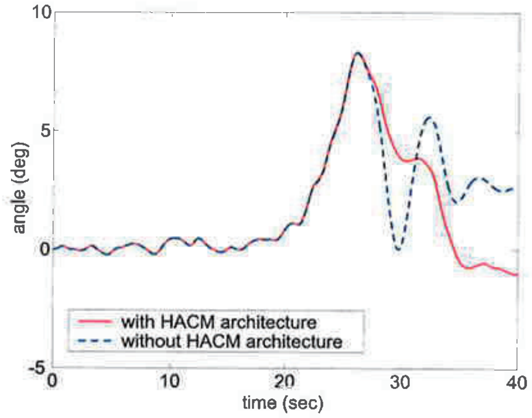


Fig. 5 Pitch angle

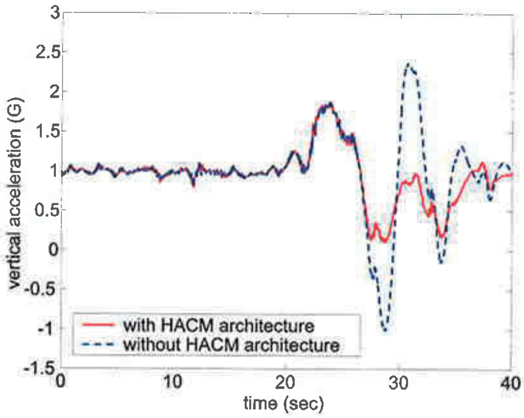


Fig.6 Vertical acceleration

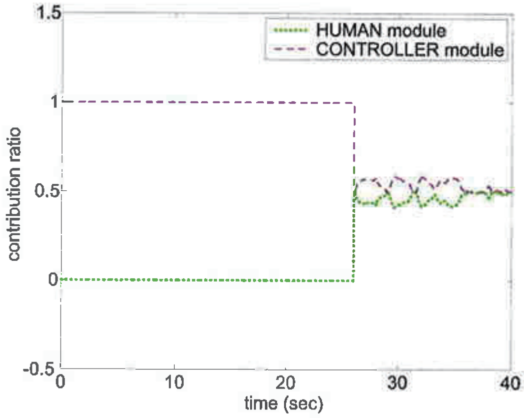


Fig. 7 Contribution ratio

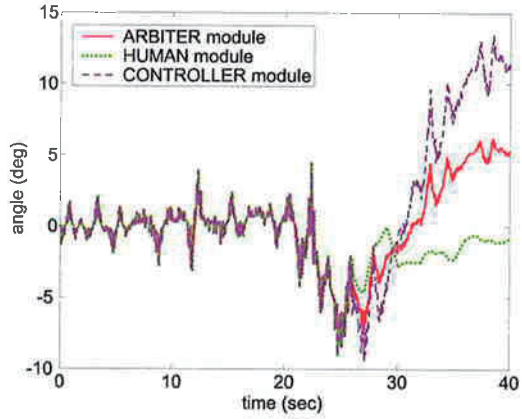


Fig. 8 Elevator angle

In order to confirm the effectiveness of the HACM architecture, we conduct numerical simulation which mimics the aircraft accident mentioned in section 2.2. Since the dynamics of the B747-400 is not officially published, this simulation uses the nonlinear dynamics of the B747-100 flying at 40,000 feet with 871 ft/sec [11]. The details of autopilot design are not disclosed, so we design an autopilot that captures the characteristics of an equipped autopilot in a distressed aircraft based on the accident analysis report. Figs. 5-8 show the effectiveness of the HACM architecture that is applied to the situation of the aircraft accident.

Fig. 5 shows that the HACM architecture works to reduce the amplitude of the pitch angle oscillation comparing with the oscillation in the accident situation. Thus, the HACM architecture contributes toward reducing the change in the vertical acceleration (Fig. 6). As shown in Fig. 6, the results of the aircraft accident show that the maximum value of the change in the vertical acceleration is around 3.4 G. On the other hand, the maximum value of the change in the vertical acceleration is reduced to around 1.1 G in the case that the

HACM architecture is applied for the same condition. This means that the HACM architecture achieves 74 % of the PIO reduction.

Fig. 7 shows the contribution ratios $\lambda_1(t)$ and $\lambda_2(t)$ are respectively given to the human module and the controller module, and Fig. 8 shows the elevator angle which the arbiter module input to the aircraft and the simulated elevator angle when the human module and the controller module are acting alone. In the arbiter module, the value of the elevator inputs from the human module and the controller module are adjusted by the contribution ratios and the arbiter module generates the elevator input given to the aircraft as shown in Figs. 7 and 8.

5 Conclusion

This paper introduced a novel architecture, the Human As a Control Module architecture (HACM architecture), which includes the human in the modular structure. Conventionally, the modular architecture contributes to mimic a human brain and is applied for the learning system/controller. On the other hand, the HACM architecture discusses the modular structure which combines the human and the artificial intelligence system.

There are two potential benefits in employing the HACM architecture. First, the use of HACM architecture allows us to realize a control system comprising the pilots and the automated flight control systems. The arbiter module adaptively adjusts the control authority between the pilot and an automated flight controller and generates an appropriate an input command to the controlled aircraft. Second, the HACM architecture has a simple framework and its algorithm comprises three types of modules—human, controller, and arbiter. Therefore, it is possible to utilize the architecture online. In addition, it is convenient to add modules with various functions to the architecture in order to develop a better automation system.

In this paper, we introduce the concept and the mechanism of the HACM architecture and applied it for the situation of the aircraft accident caused by the confliction between the automated aircraft and the pilot. It is confirmed that the proposing architecture achieves 74 % of the PIO reduction.

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